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APPLICATION, EVALUATION AND FUTURE RESEARCH POTENTIAL OF THE MATRIX- AND GRAPHBASED PRODUCT MODEL

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Keywords: design synthesis and optimisation, design methodology, product-oriented process management, matrix based product model, design structure matrix

1. Introduction

The enormous complexity of modern products as well as the increasing individualization due to different requirements of heterogeneous customers leads to steadily increasing challenges for product developers. While development and product cycles are becoming shorter, product developers have to meet the ever-increasing demands on quality, cost and functionality of products [Ponn and Lindemann 2008]. Hence, developers have to realize certain product properties by setting the appropriate characteristics [Weber 2005] in order to fulfil the requirements of customers [Luft et al. 2013c].

1.1 Problem statement and motivation

Due to these key challenges in product development and since the design problem is a multi-objective constraint satisfaction and optimization problem [Qureshi et al. 2013], product developers must be able to efficiently and effectively develop products that meet customer needs sufficiently. The behaviour of the product caused by its properties under specific usage and environmental conditions is the most important criterion when evaluating whether customers' desires and requirements are fulfilled. Following the perspective according to Weber, the definition of appropriate characteristics during the product development process is crucial. This is necessary in order to achieve the product's required property profile that arises from a variety of complex cause-effect chains, which in turn result from a set of relations [Weber 2005]. Consequently, large and complex networks between characteristics (= causes) and resulting properties (= effects) quickly occur [Luft et al. 2013c]. The complexity of today's products, particularly mechatronic products, results from the number and variety of elements and their relations, as well as from the various disciplines (e.g. mechanical or electrical engineering) involved in modern product development processes [Crostack et al. 2015].
However, even minor modifications of (one single) characteristic(s) (e.g. length, width, depth) of one component (e.g. a sealing plate of one cell module) can lead to a vast variety of changes concerning the property profile of the product (compare Luft et al. [2014a]). If the required property profile of a product is not achieved during the product development process, in practice, developers usually initiate reworks (= iterations) which influence the effects, but do not eliminate their causes. Mostly, developers are not able to identify and retrace these causes quickly and reliably due to the many different and complex dependencies between the defined characteristics and the resulting properties [Luft et al. 2013c]. Consequently, taking appropriate action alternatives is not possible because consequences neither can

be defined completely nor assessed adequately [Krehmer 2012]. Hence, this culminates in wrong decisions and unnecessary iterations, particularly in more complex structures [Luft et al. 2014b,c, 2015].

1.2 Objectives

To meet these challenges, the overall objective of the authors is to develop a suitable, computer-aided matrix and graph based product-modelling tool for a better product-oriented process management. Thus, the matrix based product model is a so-called multi domain matrix. By using this matrix based product model it is possible to map and analyse systematically all the relations between, among others, requirements, behaviours of the product and the product's properties and characteristics during the development process (see section 3 and 4). For instance, the effects of the modifications of product characteristics on product properties become visible and traceable. In addition, even differential requirements can be set into relationship with properties and characteristics of the product. Therefore, an advanced procedure model for property-based product development was proposed by Krehmer [2012] and further developed by the authors [Luft et al. 2013b,c, 2014a,b,c]. This procedure model purposefully guides developers through the development process and helps to elaborate the matrix based product model. The aim of this paper is to give a short description of this methodological and conceptual approach. We apply and evaluate it briefly in order to show future research potential. By applying this approach for several products in (industrial) case studies, the authors perform a detailed evaluation regarding the applicability, usefulness and effort of the matrix based product modelling. Afterwards, we derive directions for future research from the evaluation results (section 5).

2. State of the art and related work

The main approaches in design methodology are briefly introduced in section 2.1. Section 2.2 provides a short summary of the first results of the matrix based product-modelling approach.

2.1 Established approaches in design methodology

The manifold ways to realize the functionality in accordance with the customer's wishes enforces conceptual thinking [Schäppi et al. 2005]. Therefore, since the 1950ies, scientific research has largely focused on theoretical and methodological aspects of the development and design process [Vajna et. al 2009]. In the reasoning of Feldhusen and Grote [2013], the term of design methodology directly pertains to concrete procedures in the development and construction process of technical systems and products. These directions largely stem from the findings of construction science, cognitive psychology and experiences with different applications [Feldhusen and Grote 2013]. The goal of these procedures is to enable targeted processes, to facilitate planning and team work and to provide guidelines for product developers [Feldhusen and Grote 2013]. Consequently, the methodology of products and corresponding design processes is an important base that supports individual skills and furthers a fast and purposeful search for possible solutions [Feldhusen and Grote 2013]. Numerous approaches address these issues. They describe a holistic modelling of products and corresponding processes and the management of product and process data and information. The design methodology has received vast research attention (for an overview see [Eisenbart et. al 2007], [Geis and Birkhofer 2010], [Gericke and Blessing 2011]). In the design methodology, the following modelling methods and theories, among others, are known: the Axiomatic Design of Suh, the Concept-Knowledge Theory (C-K) of Hatchuel, the Function-Behaviour-Structure (FBS) framework of Gero, the Characteristics-Properties Modelling (CPM) of Weber and the Design Structure Matrix (DSM) methodology of Browning, Eppinger and Steward. In addition, there are also several System Modelling Languages in the field of Systems Engineering. Moreover, the quality function deployment (QFD) method of Akao helps to transform customer demands into prioritized properties and characteristics of products (compare [Romli et al. 2015]). Further approaches for modelling systems are explained in literature about graph and network theory.

2.2 Theoretical foundations regarding the matrix based product-modelling approach

The aforementioned approaches were evaluated in detail in [Krehmer 2012] and [Luft et al. 2013b] with regard to different criteria. Their analyses have shown that none of the available models is sufficiently appropriate for the challenges described in section 1.1 [Krehmer 2012], [Luft et al. 2013b].

However, these approaches consider certain aspects that were adapted for the matrix based product-modelling approach. Figure 1 illustrates the three main parts of the approach, which consist of the advanced procedure model (described in detail in [Luft et al. 2013b]), the micro-cycles of synthesis and analysis (described in detail in [Krehmer 2012]) and the matrix based product model (described in detail in [Luft et al. 2014a, b]). The advanced procedure model subdivides the product development process into 33 process steps, which directly belong to one of the four perspectives of behaviour (B), property (P), structure (S) or function (F). The left part represents the synthesis of the product from the requirements (REQ) on the overall system level (OS) through the sub system level (SS) to the properties (P) and characteristics (C) on the component level (CP). Hence, the right part displays the stepwise system integration under continuous analysis of the actual properties and behaviour on the different levels of the product architecture. In addition, the development process is divided by 16 milestones (dark borders in Figure 1) which are useful for the iteration management (e.g. targeted return points for iterations). The advanced procedure model starts on the left side with the system design and the definition of the requirements (step 1). Next, the definition of properties for all individual components (step 19) ensues, before the process proceeds on the right side from the system integration and the analysis of the achieved properties of all components (step 20) to the comparison of the realized with the required OS behaviour (step 33). After examining the fulfilment of all requirements and the property validation in the last step, the procedure model is completed.
Additionally, the micro-cycle guides the product developer through each step and fills the matrix based product descriptions with information with the help of six synthesis- and analysis-specific steps. As the information from each micro-cycle is structured and filled in the multi domain matrix (MDM), the matrix based product model is set up throughout the first 19 process steps. The matrix based product model is the last component of the approach, which is shown (in a simplified manner) in Figure 2. This matrix based product description systematically maps, among others, all the dependencies and interactions between behavioural aspects, properties, characteristics as well as requirements regarding the product. It thus provides information for the micro-cycles and controls the execution of the procedure model (e.g. the execution of iterations).

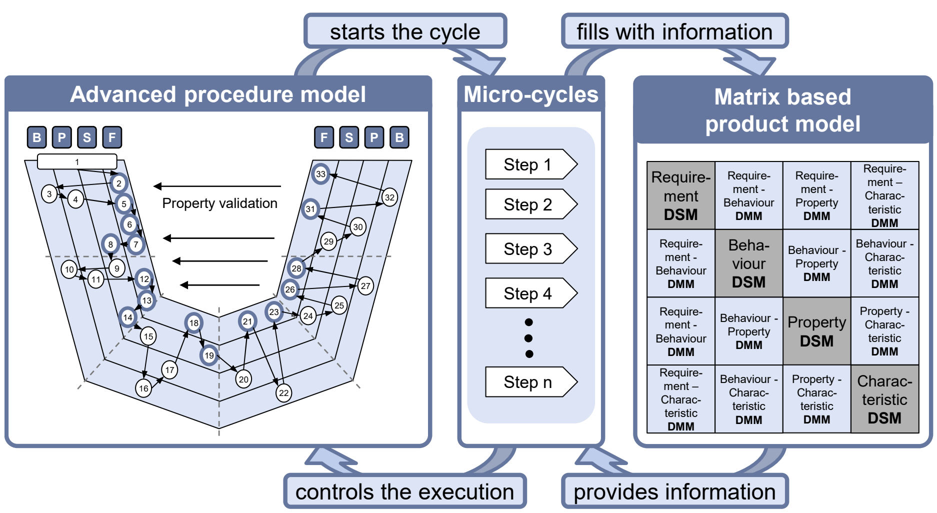

Figure 1. Interaction of the advanced procedure model and the simplified matrix based product model (compare [Luft et al. 2013c])

As a result, all product elements and their corresponding relations are modelled in the matrix based product model. The product model consists of all the requirements, the various behavioural aspects, properties, function structures (FS) and active principle structures (AS) of the overall system and the subsystems as well as of the all the characteristics of the individual components. It hence equals a multi domain matrix which is composed of a variety of design structure matrices (DSM), which describe relationships between two elements of the same domain (e.g. characteristic-characteristic-matrix), and design mapping matrices (DMM), which describe relationships between two elements of different domains (e.g. characteristic-property-matrix). In the simplified and schematic matrix based product model (see Figure 2) each matrix field (e.g. a characteristic-property-matrix) is an n × m matrix. If necessary (e.g. for more complex products), the matrix based product model can be flexibly expanded to more subsystem levels. Consequently, it is possible to structure the overall system, for example, in subsystems, modules and submodules.

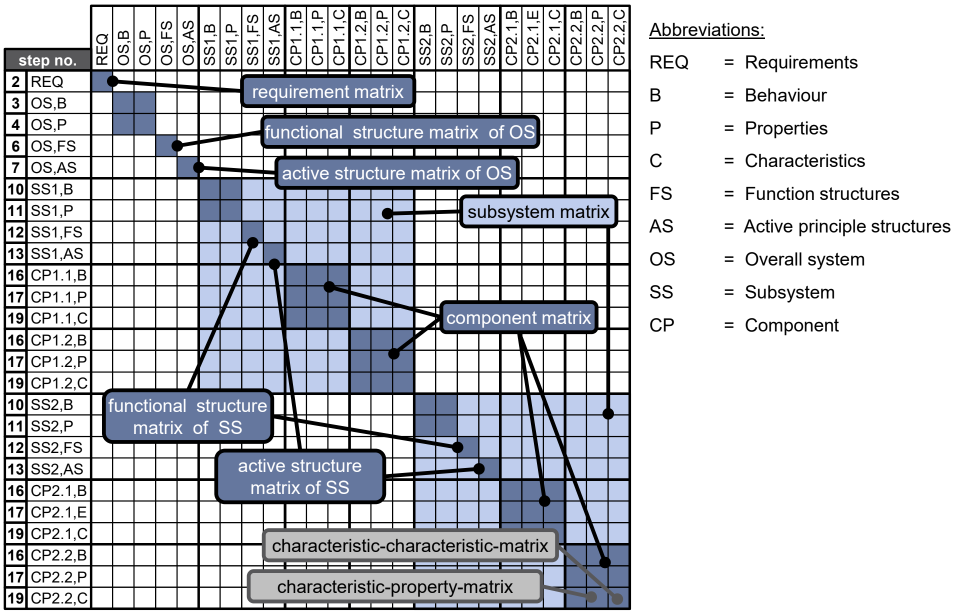

Figure 2. Simplified structure of the matrix based product model [Luft et al. 2014a]

Developers have to create characteristic-property matrices for all components because properties can only be realized through the determination of certain characteristics [Weber 2005]. Subsequently, all required characteristics (e.g. radius, material) are defined for the individual components (e.g. wheel hub) in characteristic-characteristic matrices. Thereby, the effects of characteristic changes on product properties become visible and traceable. Furthermore, the matrix based product model sets all the different requirements into relationship with the properties and characteristics of the product at the OS-level, the SS-level and CP-level. As a result, the relations between characteristics, properties and the resulting behaviours and other elements of the product model are modelled systematically.

Another advantage is the simple transformation of the matrix bases in a graph based product model. By doing so, the complex networks between characteristics (cause) and properties (effect) as well as between characteristics and properties among themselves are visualized in a structured way (Figure 3). Furthermore, path algorithms can be used to trace the relations between several product elements (Figure 3). In addition, the product model supports developers in several ways. For instance, in the case of a change request (e.g. modified requirement REQ 3), the identification of the affected product elements, such as the properties of the overall system (e.g. OS,P 2), of the subsystem (e.g. SS,P 2 and 5) and of components (e.g. CP,P 1, 3, 6) is supported. This allows developers to purposefully decide which characteristics of which components should be modified (e.g. CP,C 1, 2). To sum up, the matrix and graph based product model supports developers in taking targeted action alternatives during the development process. This results from the fact that all the dependencies and interactions between the product elements can be modelled, analysed and visualized. Therefore, all effects of the modification of product elements can be estimated by using of the matrix and graph based product model.

3. Application of the matrix based product model

The matrix based product modelling approach is first applied on component level of a bicycle frame (section 3.1.). Thereafter, the approach is explained on subsystem level in section 3.2. This is illustrated by using a characteristic-(subsystem-)property-matrix for chassis parameters of a car.

3.1 Application of the matrix based product model on component level

This chapter focuses on the application of the matrix based product model by means of the example of a bicycle frame. Apart from the frame, the bicycle is basically composed of a steering unit, a drive unit, a saddle, brakes, lights and wheels. The frame consists of two sub-modules which are the front module (top tube, head tube, seat tube and down tube) and the rear module (seat stays, chain stays and dropouts back). The steering unit includes the fork (fork steerer, fork head, and fork blades, dropout front) and the handlebar (handlebar stem, stem). Due to the large number of components and their characteristics and properties, the simplified matrix based product model presented in Figure 4 only focuses on the top tube and seat tube of the front part as well as on the welded joint between them.

The relations between the characteristics and properties are modelled by corresponding entries in the rows and columns (compare Figure 4). By analysing a product element in a row, it is easy to find out which elements in the columns are affected by this particular product element. For instance, the length of the top tube (T3) affects the seat tube angle of the front module (F3) and the mass centre of the top tube (T1). In addition, it is also possible to identify which of the elements in the rows influence one element in a column. For instance, the length of the top tube, the top tube's inner diameter and outer diameter are influencing the mass centre of the top tube.

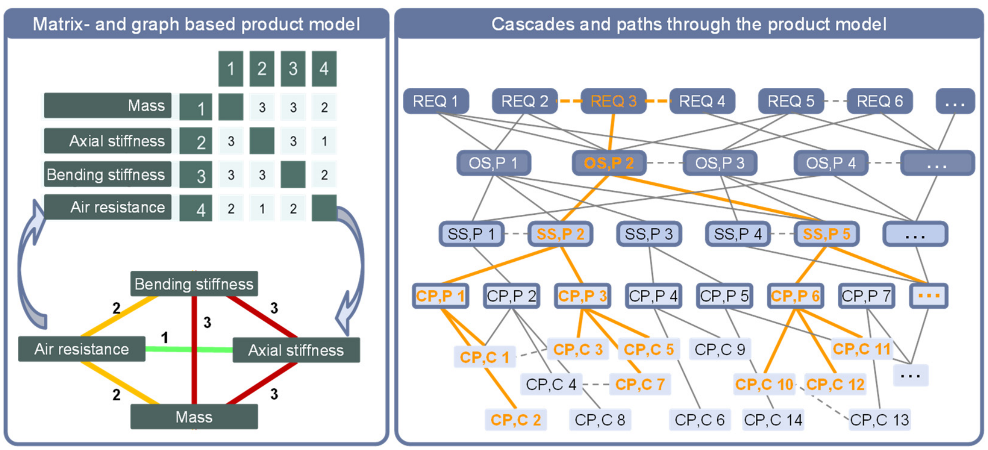

Figure 3. Transformation between an exemplary matrix and graph based product model (left) and simplified representation of relations in the graph based product model (right)

By using, for example, a characteristic-property matrix, it can be analysed which unintended effects on properties have proposed modifications to certain characteristics. Here, different types of dependencies or interactions can be distinguished from each other. Influences and dependencies between two characteristics are ordinarily marked with an “x” (usually on both sides of the diagonal). In this case, it is not possible to indicate the direction of the dependency since it is not possible to distinguish whether characteristic A is dependent on characteristic B or if characteristic B is dependent on characteristic A. In contrast to “x”, the direction of the dependency can be specified by a plus sign (e.g. “+1”) or a minus sign (e.g. “-1”). For instance, a negative directed relation (“-1”) exits when the value of a dimensional characteristic increases and as a result, the value of a (geometrical) property decreases [Luft et al. 2013c]. In addition, the intensity or strength of a relation is modelled with numerical numbers (e.g. "-3") [Luft et al. 2014a,b].

3.2 Application of the matrix based product model on subsystem level

After setting up all matrices for the (mechanical) components of a front wheel suspension regarding their physical-chemical and geometric characteristics and their corresponding properties [Luft et al. 2014a,b], its structural design has to be modelled in the next step. Therefore, an appropriate matrix based product model for the kinematics of the chassis (SS), which has a significant impact on the driving behaviour of the vehicle (OS), is used. For this purpose, a simplified structure of a characteristic-(subsystem-)property-matrix for chassis parameter is illustrated in Figure 5.

		Frame (FR)																								
		Front module (F)																								
						Top tube (T)							Welded joint (W)							Seat tube (S)						
	Row influences column	F1	F2	F3	F4	T1	T2	T3	T4	T5	T6	T7	W1	W2	W3	W4	W5	W6	W7	S1	S2	S3	S4	S5	S6	S7
Front module (F)	F1- P | Bending stiffness																									
Front module (F)	F2- P | Mass centre																									
Front module (F)	F3- P | Seat tube angle	x																								
Front module (F)	F4- C | Position and orientation			x																						
Top tube (T)	T1- P | Mass centre		x																							
Top tube (T)	T2- P | Bending stiffness	1																								
Top tube (T)	***T3- C | Length***			x		x																				
Top tube (T)	T4- C | Inner diameter					x	x																			
Top tube (T)	T5- C | Outer diameter					x	x						1	1												
Top tube (T)	T6- C | Value of E-modulus, R_m	x					x																			
Top tube (T)	T7- C | Material compatibility														1											
Welded joint (W)	W1- P | Bending stiffness	1																								
Welded joint (W)	W2- P | Weld seam length																									
Welded joint (W)	W3- P | Weldability																									
Welded joint (W)	W4- C | Weld type												x		x											
Welded joint (W)	W5- C | Weld size												1		x											
Welded joint (W)	W6- C | Filler metal														x											
Welded joint (W)	W7- C | Values of filler metal												x		x											
Seat tube (S)	S1- P | Mass centre		x																							
Seat tube (S)	S2- P | Bending stiffness	1																								
Seat tube (S)	S3- C | Length																			x						
Seat tube (S)	S4- C | Inner diameter																			x	-1					
Seat tube (S)	S5- C | Outer diameter												1	1						x	x					
Seat tube (S)	S6- C | Value of E-modulus, R_m	x																			x					
Seat tube (S)	S7- C | Material compatibility														1											

Abbreviations:

FR = Frame
F = Front module
T = Top tube
S = Seat tube
W = Welded joint
P = Property
C = Characteristic

Figure 4. Simplified matrix based product model of a bicycle frame [Crostack et al. 2015]

Characteristic-(subsystem-)property-matrix (extract)	Properties of the subsystem										
Structural characteristics	Spread	Track width	Roll pole	Roll center	Camber	Self-steering offset	Castor angle	Kinematic trailing route	Lateral force lever arm	Toe in	Kingpin offset
Point wishbone top front			x	x							
Point wishbone top rear			x	x							
Point wishbone down front			x	x							
Point wishbone down rear			x	x							
Steering axle YZ	x										x
Steering axle XZ						x	x	x	x		
Point track width Y		x		x				x	x		
Wheel centre axle YZ					x						
Centre point of the wheel axle						x	x	x	x		x
Wheel centre axle XY										x	

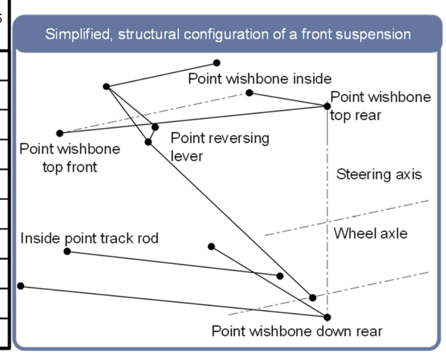

Figure 5. Characteristic-(subsystem-)property-matrix for chassis parameter (simplified extract)

The subsystem as well as the overall system properties result from the definition of the values of the corresponding structural characteristics (e.g. distances to the origin coordinate system, points, axes, angles). By specifying the structural characteristics, the matrices of the component can be integrated into the superordinate subsystems. Thereafter, the subsystems are integrated into the overall system by defining the structural characteristics between the subsystems. For this purpose, a first skeleton of kinematics has to be created before or during the design of the components. In this skeleton, the spatial positions of the pivot or hinge points or axles are modelled. Thereby, a point in the skeleton corresponds to the cross point of two components. The use of CAD systems is suitable for the creation of the skeleton due to spatial dimensions. The properties of the subsystems (e.g. the suspension) can be adjusted by

changing the position of the corresponding components with the help of the (different possible) modifications of structural characteristics (see Figure 5).
A relation represented by an "x" in the matrix exists if the definition of a property (of the subsystem) or a suspension parameter requires a structural characteristic. Reading the matrix in Figure 5 from row to column, the following question is answered: Which properties (parameters) are changing if a particular characteristic is modified? By contrast, while reading from column to row, the matrix indicates which characteristics need to be changed if parameters of the chassis should be varied.

4. Evaluation of the matrix and graph based product modelling approach

The presented product modelling approach was compared with other research approaches by the authors as well as together with researches from other institutes. A comparison with the CPM approach (with the further development by Crostack) is carried out in section 4.1. The evaluation of IT tools for modelling and visualizing the matrix based product model is described in section 4.2.

4.1 Comparison with other product modelling approaches

The evaluation is based on a relative comparison of the matrix and graph based product modelling (MGPM) approach with the CPM approach of Weber (including its further development by Crostack). Thereby, for both approaches an ideal approach was taken into account. An ideal approach is theoretically possible approach that optimally fulfils all criteria. The following results are based on a literature review of the CPM and the matrix and graph based product modelling approach as well as on practical experience from its application. For the qualitative assessment, a 5-point scale with the expressions "very good", "good", "medium", "bad" and "very bad" is selected. This scale gives neutrality with respect to an optimization direction. For instance, if the criterion effort is evaluated as very bad, it has to be regarded as very high (compare [Crostack et. al 2015]).

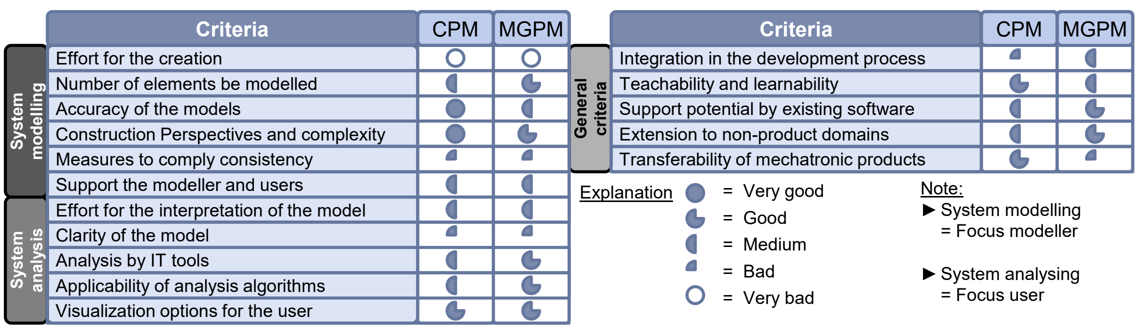

Figure 6. Results from the comparison with the CPM approach [Crostack et. al 2015]

After the jointly conducted comparison, the authors were able to demonstrate that the benefits of both approaches can be linked together. Based on the analysis of these two approaches, the matrix- and graph based product modelling is used as a basis for an improved and expanded approach for product modelling. This advanced approach is extended by certain aspects of the CPM approach, which are described in detail in [Crostack et. al 2015]. For the further development of the approach presented in this paper, both approaches have to be also compared with other existing approaches (see section 2.1). As a result, weaknesses were identified and potential for improvements was derived.

4.2 Evaluation of tools for modelling and visualizing matrix and graph based product models

Product models in industrial practice include far more elements than the simple examples for illustration purposes in the previous chapters. While for a matrix based product model with 10 elements, only 90 decisions are necessary for filling out the potential relations. If a matrix should include 30 elements, there are already 870 decisions required in order to represent each possible relation [Lindemann et al. 2009]. As a result, the described systematic approach for setting up the structure of a matrix based product model with its elements and dependencies is particularly prone to errors and time-consuming. Consequently, a computer-aided support is useful and essential.

For this reason, the authors analysed many IT tools, which can support the modelling, analysing and visualizing of product models. These IT tools are subdivided into freely available and commercial applications (see Figure 7). Some of the used evaluation criteria for an initial assessment of the applicability of the several IT tools are also in Figure 7. It is important to know that the following presentation of the evaluation results in Figure 7 is only a highly simplified summary of the very detailed evaluation conducted by the authors.

		System modelling					System analysis					General criteria			
		Customization	CAX capability	Interfaces	Types of matrices	Types of relations	Analysis of nodes and edges	Analysis of subsystems	Indirect dependencies	System representation	Specialization	Costs	Training and implementation	Additional functionality	Programming interface (API)
Free software	Cambridge Advanced Modeller	+	-	+	-	+	+	+	-	+	+	+	+	+	+
	EXCEL Macros for Partitioning and Simulation	O	-	+	-	O	O	O	-	O	+	+	O	O	+
	MATLAB Macro for Clustering	+	-	O	-	O	-	O	-	-	+	+	O	-	-
Commercial software	IntelliJ IDEA	O	-	na	-	+	na	O	-	O	-	O	+	na	na
	Lattix	O	-	na	+	na	+	+	-	+	-	-	na	+	na
	SonarJ	O	-	na	-	na	na	O	-	+	-	na	+	O	na
	Structure 101	O	-	na	-	O	na	na	-	na	-	O	O	na	na
	Adept Design Software Suite	O	-	na	-	na	na	na	na	-	O	-	na	na	na
	Plexus	O	-	O	-	na	O	O	na	+	O	-	+	O	na
	Project DSM	-	-	na	-	na	O	O	-	O	O	-	O	na	na
	LOOMEO	+	-	O	+	+	+	O	+	+	+	-	+	O	-
	Acclaro DFSS	+	-	O	-	+	na	O	-	na	+	-	+	+	na
	iPRIME NAVI	O	-	na	-	na	-	O	-	O	O	-	na	O	-

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Figure 7. Evaluation of IT tools for matrix and graph based product modelling

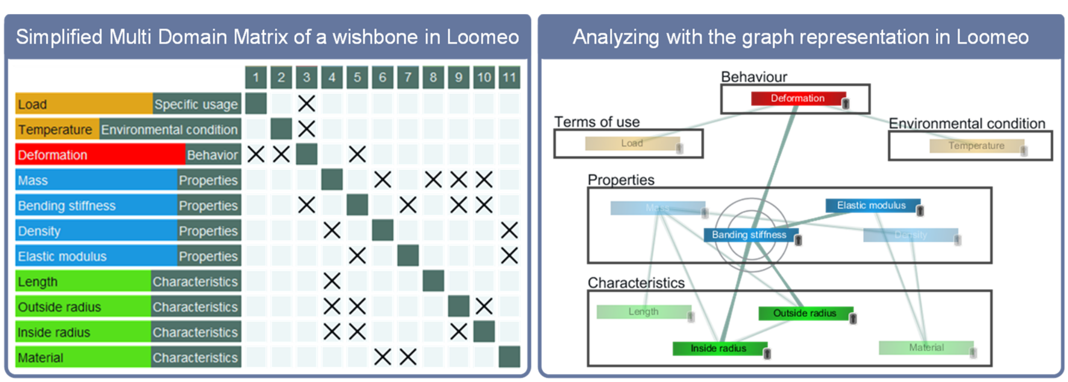

Figure 8. Matrix and graph based representation of the product model [Luft et al. 2014a]

LOOMEO is a commercial software with a good evaluation result. This software has a focus on structural complexity management. It is particularly used for documentation, visualization and analysis of complex dependencies between different elements. By using matrices, force-directed graphs and diagrams of system elements and their dependencies are represented and manipulated. LOOMEO also allows developers to create a MDM-structure because this software is based on the terminology of DSM-methodology. LOOMEO provides, alternatively to the matrix representation, a graph representation in which nodes and edges are represented in graphical form (Figure 8). The interpretation of the graph based visualization by the product developer is much more intuitive. Hence, it is more suitable to get a "picture" of the whole product model with all its elements and relations.

5. Conclusion and future research

The proposed matrix based product model is based on a structured outline of the properties. It furthermore highlights the consequences of the determination of properties and the resulting behaviour of the product. The comparisons between target and actual properties indicates whether the desired properties are already sufficiently realized or whether iterations are necessary [Luft et al. 2014c]. Moreover, the determined dependencies outline which unintended consequences impact upon intended modifications of characteristics. Therefore, it is necessary to identify which non-directional or directional dependencies of properties belong to which characteristics and how the product behaves under the given conditions of use and different environmental influences. Due to the detailed modelling of all product elements, like properties and characteristics, the matrix and graph based product model is extremely time-consuming for complex products. As it is also challenging to keep the overview of complex relations (and relations chains, see Figure 3), it is possible to "get lost" in the matrices. However, the repeated application of the product model allows adaptations and thus takes less time. Moreover, some practical examples have shown that this matrix based product model enables developers to work in a more structured, goal-oriented and efficient way. Furthermore, it avoids iterations preventively. Consequently, the authors deem first analyses on basis of the matrix based product model as promising. Finally, this approach allows identifying the number of possible dependencies between the components by analysing the network of geometric characteristics. Consequently, the presented application example suggests that the benefit of the matrix and graph based model surpasses its relatively high expenditure.

In future research, the authors will focus on further ameliorations of the procedure model for the property-based product development. They furthermore seek to validate their approach in additional practical use cases. In this respect, it also seems promising to explore the integration of product elements from other disciplines (e.g. electronics and computer engineering) in the matrix based product model. In addition, the further application and evaluation of existing software tools (e.g. LOOMEO, Cambridge Advanced Modeler) with regard to their suitability for supporting developers in modelling a matrix based model is an important future task. Besides that, the authors work on the realization of an appropriate interface between the matrix based product model and CAD- and PLM-systems, respectively. In addition, approaches from the Systems Engineering (e.g. SysML) are analysed. These may help in the creation of partial matrices. It is the aim of the authors to reduce significantly the effort needed to create matrices and to improve the visualization of the dependencies between properties and characteristics. The latter aspect is particularly important as a better graphical presentation as well as network-like representation may contribute to further valuable application possibilities (compare e.g. [Luft et al. 2013a]).

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